U. of Iowa 67-67

A CINEMATOGRAPHIC DISPLAY OF OBSERVATIONS OF LOW-ENERGY PROTON AND ELECTRON SPECTRA IN THE TERRESTRIAL MAGNETOSPHERE*

By

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November 1967

*Research supported in part by the National Aeronautics and Space Administration under Grant NsG-233-62 and Contract NAS5-2054 and by the Office of Naval Research under Contract Nonr-1509(06).

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Abstract

A massive series of observations of the differential energy spectra of proton and electron intensities over the energy range ~ 300 eV to 50 keV within the earth's magnetosphere and its environs has been obtained with an array of electrostatic analyzers borne on the earth-satellite OGO 3. In order to supplement the presently existing publications derived from these observations and to provide further insight into the distributions of low-energy charged particles within the earth's radiation zones over geocentric radial distances ~ 2 to 20 R_E (R_E, earth radii) we have utilized a SC 4020 microfilm plotter to construct a cinematographic display of the differential energy spectra of proton and electron intensities which spans a complete circuit of the spacecraft around the earth, or ~ 50 hours of substantially continuous observations beginning at 1330 U.T. on July 14, 1966. This cinematographic display comprises approximately 18,000 individual frames and summarizes some 550,000 intensity measurements. A description of the methods and graphic results is furnished as an aid in interpretation of this visual presentation of the observations.

Introduction

Progress in space science technology over the past several years has been reflected in rapidly increasing collections of raw observations of such phenomena as the terrestrial radiation belts, terrestrial and interplanetary magnetic fields, solar plasmas in the interplanetary medium, and solar X-ray emissions. Accompanying this increasing telemetry capability are the greater tasks of organization, presentation and analyses of these truly massive amounts of information. For example, in 1962 a typical array of G.M. tubes for measurements of charged particle intensities within the outer radiation zone flown on Explorer 14 [Frank, 1965a] provided approximately 200 detector samples per hour; this telemetry rate can be compared with the capabilities of a current OGO spacecraft for a similar experiment [Frank, 1966a] of approximately 230,000 detector samples per hour. In order to complement graphic displays of our observations and to promote further insight into the spatial distributions and temporal behavior of low-energy proton and electron intensities ($300 \text{ eV} \lesssim E \lesssim 50 \text{ keV}$) within the earth's magnetosphere and its environs we have constructed a cinematographic presentation of charged particle spectra observed during a typical orbit of the OGO 3 spacecraft. This cinematographic display creates a new, and quite valuable, impression of the magnetospheric population of low-energy charged particle intensities when compared to standard graphic displays such as charged particle intensities as functions of geocentric radial distance, time, etc. The methods invoked in the production of this 'motion picture' survey of the magnetosphere are discussed herein.

Production of the Cinematographic Display

The overall goal of the present task is to summarize approximately 50 hours of satellite observations of low-energy charged particle intensities in the earth's magnetosphere, or some 550,000 detector samples, in a useful, brief yet comprehensive, visual display. Measurements of the proton and electron differential energy spectra over the energy range $\sim$ 300 eV to 50 keV were obtained recently with an array of electrostatic analyzers borne on the earth-satellite OGO 3. A description of the orbit and of the electrostatic analyzer array and analyses of the observations of these low-energy charged particles have been previously given by Frank [1967a, b, c, d, e]. Several salient features of this instrumentation are recalled here as a convenience to the reader. OGO 3 (1966-49A) was launched on 7 June 1966 into a highly eccentric orbit with apogee 128,500 km and perigee 6,700 km geocentric radial distances, inclination 31° and period 48.6 hours. At launch the local time of the direction from the center of earth to spacecraft apogee position was $\sim$ 22:00. On 14 July the local time of the direction of the line of apsides was nearly 20:30. A composite system of reaction wheels and gas jets provided a predetermined, monitored orientation of the various spacecraft-referenced coordinates with respect to the directions from the satellite to earth and the sun and with respect to the orbital plane. The University of Iowa instrumentation includes four cylindrical-plate electrostatic analyzers to select charged particle energy and continuous channel multipliers (Bendix 'channeltrons') as charged particle detectors. Each of the two pairs of electrostatic analyzers provides simultaneous measurements of the directional intensities of protons and electrons, separately, within the same energy bandpasses over an energy range extending from approximately 300 eV to 50,000 eV. The directions of the fields of view of these two pairs of analyzers, designated as LEPEDEA's 'A' and 'B' (LEPEDEA, Low Energy Proton and Electron Differential Energy Analyzer), are orthogonal and are directed parallel to spacecraft body Cartesian axes, +Z (toward earth during normal spacecraft operations) and +Y, respectively. The directions of the field of view of LEPEDEA 'A' in several pertinent coordinate systems during the series of observations presented in the visual display are summarized in Table I. All four electrostatic analyzers, two Geiger-Mueller tubes, and curved-plate voltage monitors (a calibration sample for each pair of proton and electron measurements) time-shared the experiment 15-bit accumulator in a complex, but tractable, manner. The contents of this accumulator were telemetered once each 1.15, 0.144 or 0.018 seconds for the three possible spacecraft data rates, 1,8 or 64 kilobits $(sec)^{-1}$, respectively. More detailed descriptions of this instrumentation have been given previously by Frank [1965b, 1967a].

The format of the cinematographic display is depicted in

Table I

Coordinates for the Axis of LEPEDEA 'A' Field of View

14-16 July 1966

OGO 3

DAY (July)	U.T.	Satellite Position, geocentric radial distance (earth radii)	Axis directed along: Solar-ecliptic θ_{SE}	Solar-ecliptic φ_{SE}	Solar-magnetospheric θ_{SM}	Solar-magnetospheric φ_{SM}	Pitch-angle* α^+
14	16:52	20	-40°	302°	-34°	299°	115°
15	00:01	18	-38°	311°	-40°	312°	135°
15	03:32	16	-37°	316°	-32°	313°	133°
15	06:03	14	-35°	320°	-26°	315°	123°
15	08:04	12	-33°	325°	-22°	318°	111°
15	09:44	10	-31°	330°	-20°	322°	98°
15	11:09	8	-28°	337°	-18°	329°	86°
15	12:20	6	-23°	345°	-17°	338°	73°
15	13:16	4	-14°	356°	-13°	352°	60°
15	14:03	2	9°	24°	3°	25°	41°
15	14:58	2	-8°	202°	-3°	203°	135°
15	15:46	4	-28°	231°	-20°	234°	141°
15	16:42	6	-34°	244°	-27°	246°	142°
15	17:52	8	-38°	254°	-33°	255°	143°
15	19:18	10	-39°	262°	-38°	262°	144°
15	20:58	12	-40°	268°	-42°	268°	146°
15	22:54	14	-41°	274°	-42°	274°	148°
16	01:25	16	-41°	279°	-40°	279°	146°
16	05:17	18	-41°	285°	-30°	283°	136°
16	12:25	20	-41°	296°	-23°	290°	111°

*Magnetic field model: Jensen and Cain [1962].

+Convention: if $\vec{v} \parallel \vec{B}$, $\alpha = 0°$

Figure 1 which is a reproduction of one of the frames of the 'motion picture'. In the upperhand half of this frame is summarized the spacecraft position in a geocentric radial distance-geocentric local time coordinate system. As a further reference for the viewer the average positions of the magnetopause and transition shock as surveyed with the IMP 1 magnetometer [Ness, Scearce and Seek, 1964] have been included in each frame. The position of the spacecraft at the time of observations summarized in Figure 1 lies near the average magnetopause position in the upper left-hand quadrant; the trace of the orbit is nondestructive, or is accumulated as time progresses from the initial frame (see Figures 1 through 8 which are in chronological order). The date and U.T. (hour, minute) of each frame, L-shell as derived from Jensen and Cain [1962] coefficients for the magnetic field and magnetic latitude λ are provided at the midleft-hand side of each frame. The lower half of Figure 1 displays proton and electron differential energy spectrums over the energy range $\sim 3 \times 10^2$ to 5×10^4 eV. Both abscissa and ordinate scales are logarithmic and the ordinate units are particles $(cm^2\text{-sec-sr-ev})^{-1}$. The cinematographic display comprises approximately 18,000 frames such as the frame reproduced in Figure 1 spanning the period 13:31 U.T. on 14 July 1966 through 15:21 on 16 July. Hence if the projection rate is 24 frames$(sec)^{-1}$ these fifty hours of substantially continuous observations ($\sim$ 550,000 transmitted detector samples) can be visually displayed in approximately 12.5 minutes.

In order to effect a visually continuous variation in the spectral profiles it was necessary to interpolate between the 'discrete' observations of proton and electron differential energy spectra. The time reduction was chosen to be 12.5 seconds real time between each frame for $L \geq 6.0$ and 2.5 seconds real time between each frame for $L < 6.0$. If the projection rate is 24 frames$(sec)^{-1}$ then the interval between two consecutive satellite observations of charged particle spectra is 1 second display time for $L \geq 6.0$.

Several of the mathematical details of this interpolation are of interest in the interpretation of the results. If $j(E_i, t_o)$, $i = 1, 2, \ldots, 13$, denotes the directional differential intensity of charged particles at energy E_i and time t_o, then the interpolated intensities between times t_o and $t_{24} = t_o + 300$ seconds (real time) and for $L \geq 6.0$ are

$$j(E_i, t_k) = j(E_i, t_o) + \frac{12.5k}{300}(j(E_i, t_{24}) - j(E_i, t_o)),$$

where $k = 1, 2, \ldots 24$. If $j(E_i, t_{24})$ was not telemetered or was not resolvable above background responses of the instrumentation, for example, then a 'false' value $j'(E_i, t_{24})$ was substituted such that

$$j'(E_i, t_{24}) = j(E_n, t_{24})$$

where E_n is chosen such that $|E_n - E_i|$, $n = 1, 2 \ldots 13$, $n \neq i$, is a minimum (i.e., next available energy channel). The x-axis (energy) range of the eventual polynomial fit is accordingly varied as

$$E_i' = E_i + \frac{12.5k}{300} (E_n - E_i)$$

and

$$j'(E_i, t_k) = j(E_i, t_o) + \frac{12.5k}{300} (j'(E_i, t_{24}) - j(E_i, t_o)),$$

and finally

$$j'(E_i', t_k) = j'(E_i, t_k) + \frac{(E_i'-E_i)}{(E_n-E_i)} (j(E_n, t_k) - j'(E_i, t_k)).$$

If $j(E_i, t_o)$ is unavailable then a similar procedure is invoked and the range of the polynomial fit correspondingly increases with increasing time. The intensities $j(E_i, t)$, $j(E_{i+1}, t)$, $j(E_{i+2}, t)$ and $j(E_{i+3}, t)$, $i = 1, 2, . . . 10$, were then fit with a series of third degree polynomials $P_i(E)$. These approximations were found to provide adequate representation of the observed electron and proton spectra within the instrumental accuracy. The 'Newton's divided difference interpolation formula' was utilized to determine the coefficients of the polynomials. All processing of the observations and programming of this cinematographic display were performed at the University of Iowa and plot tapes were generated with an I.B.M. 7044 computer; production of the display was executed via an SC 4020 at the Goddard Space Flight Center with the kind cooperation of Dr. G. H. Ludwig.

Discussion of Selected Frames of the Cinematographic Display

A series of selected frames reproduced from the cinematographic display and ordered chronologically are shown in Figures 1 through 8. The directional differential spectrum of electron intensities near satellite apogee position displayed in Figure 1 features a peak of intensities at $\sim$ 25 keV. Such a feature of the electron spectrums in the geomagnetic tail region has previously been found by Frank [1967a] and is prominent in the present visual summary of observations. In fact the largest changes of electron intensities occur at electron energies exceeding several kiloelectron volts. Severe temporal variations of electron and proton spectra are characteristic of this region (see Figures 1, 2, 7 and 8). The secondary maxima of differential intensities of protons and electrons (see, for example, the electron relative maximum intensities at 25 keV, 12 keV and 10 keV of Figures 1, 2 and 8, respectively, and the proton relative maximum intensities at 2.5 keV and 2 keV of Figures 2 and 8, respectively) appear to occur at monotonically decreasing energies with increasing time, appearing much like a 'ripple' moving up the bulk of the spectrum. The inner and outer radiation zone spectra shown in Figures 3, 4 and 5 are limited in energy range when the electrostatic analyzer responses were predominantly attributable to penetrating and scattered energetic

($E \gtrsim 100$ keV) charged particles. The electron spectrum presented in Figure 6 is typical of those observed in the region in the local night hemisphere of the magnetosphere over $L \simeq 8$ to 12 originally surveyed by Gringauz and his colleagues [1960]. The rapid decrease in intensities below $\sim 10^4$ electrons $(cm^2\text{-sec-sr-ev})^{-1}$ with decreasing electron energy for $E_e < 1$ keV and the secondary, minute maximum at 350 eV are residuals of the polynomial fit and should not be interpreted as representing the electron spectrum within this energy range. All other proton and electron spectrums included in the visual display are not invalidated by this limitation. Of further interest is the proton spectrum over $20 \leq E \leq 45$ keV shown in Figure 3 which is the low-energy 'tail' of energetic proton ($E \gtrsim 100$ keV) spectra in the outer radiation zone [Davis, 1965].

Availability of 'Motion Picture'

The cinematographic display has been reproduced on 16 mm film suitable for use with ordinary movie projectors. At a projection rate of 24 frames $(sec)^{-1}$ the duration of the visual display is $\sim$ 12.5 minutes. Several copies of this film have been acquired and are available for short-term loan upon written request to this laboratory.

Acknowledgments

The authors are indebted to Dr. G. H. Ludwig of the Goddard Space Flight Center for his cooperation toward allowing us to use the SC 4020 microfilm plotter at G.S.F.C. and to Dr. J. A. Van Allen for his support throughout various phases of this research. This research was supported in part by the National Aeronautics and Space Administration under Grant NsG-233-62 and Contract NAS5-2054 and by the Office of Naval Research under Contract Nonr-1509(06).

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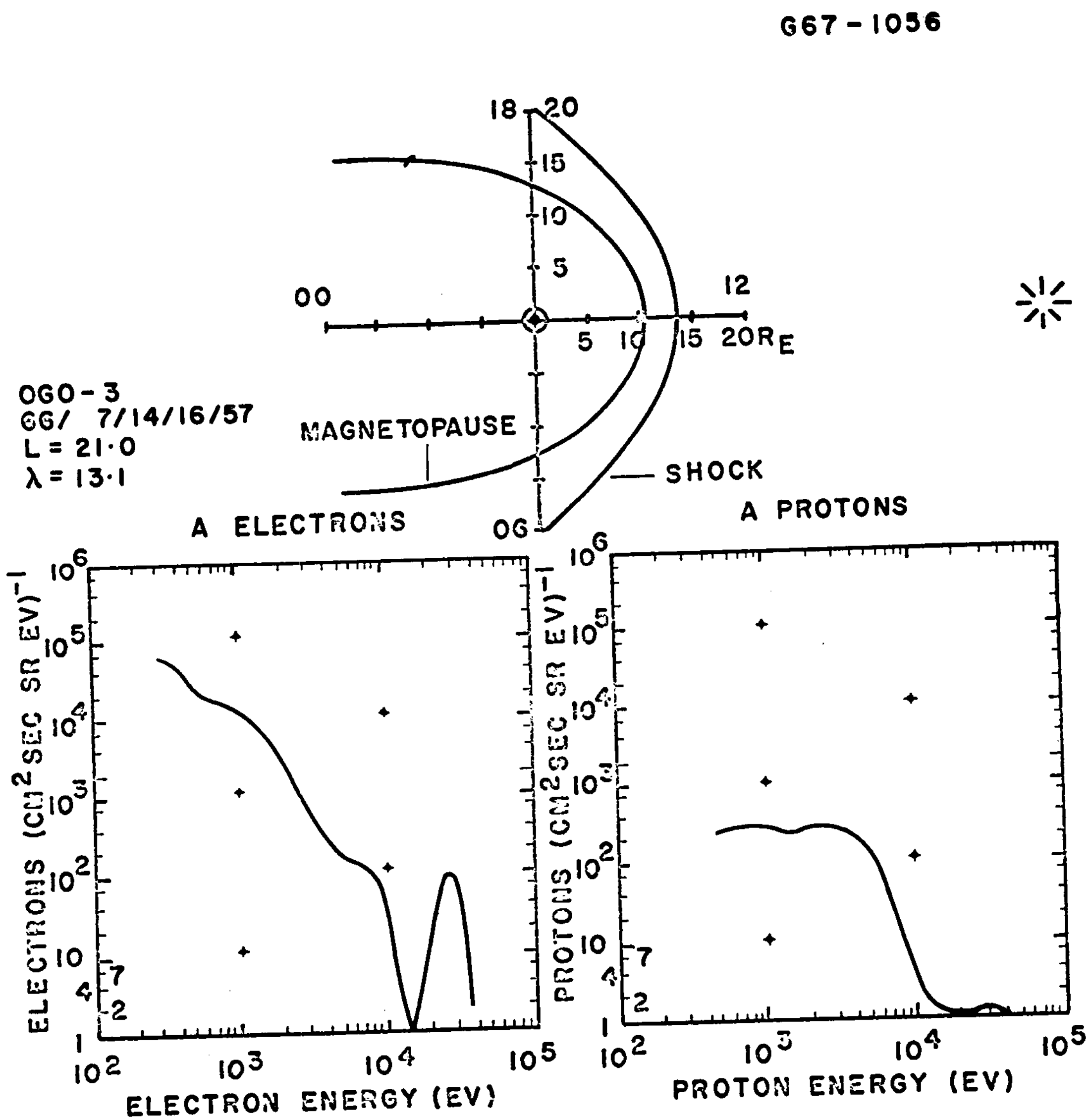
G67 - 1056
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GG/ 7/14/16/57
L = 21·0
λ = 13·1
MAGNETOPAUSE
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A ELECTRONS
A PROTONS
ELECTRONS (CM²SEC SR EV)⁻¹
PROTONS (CM²SEC SR EV)⁻¹
ELECTRON ENERGY (EV)
PROTON ENERGY (EV)

Figure 1

G67-1057

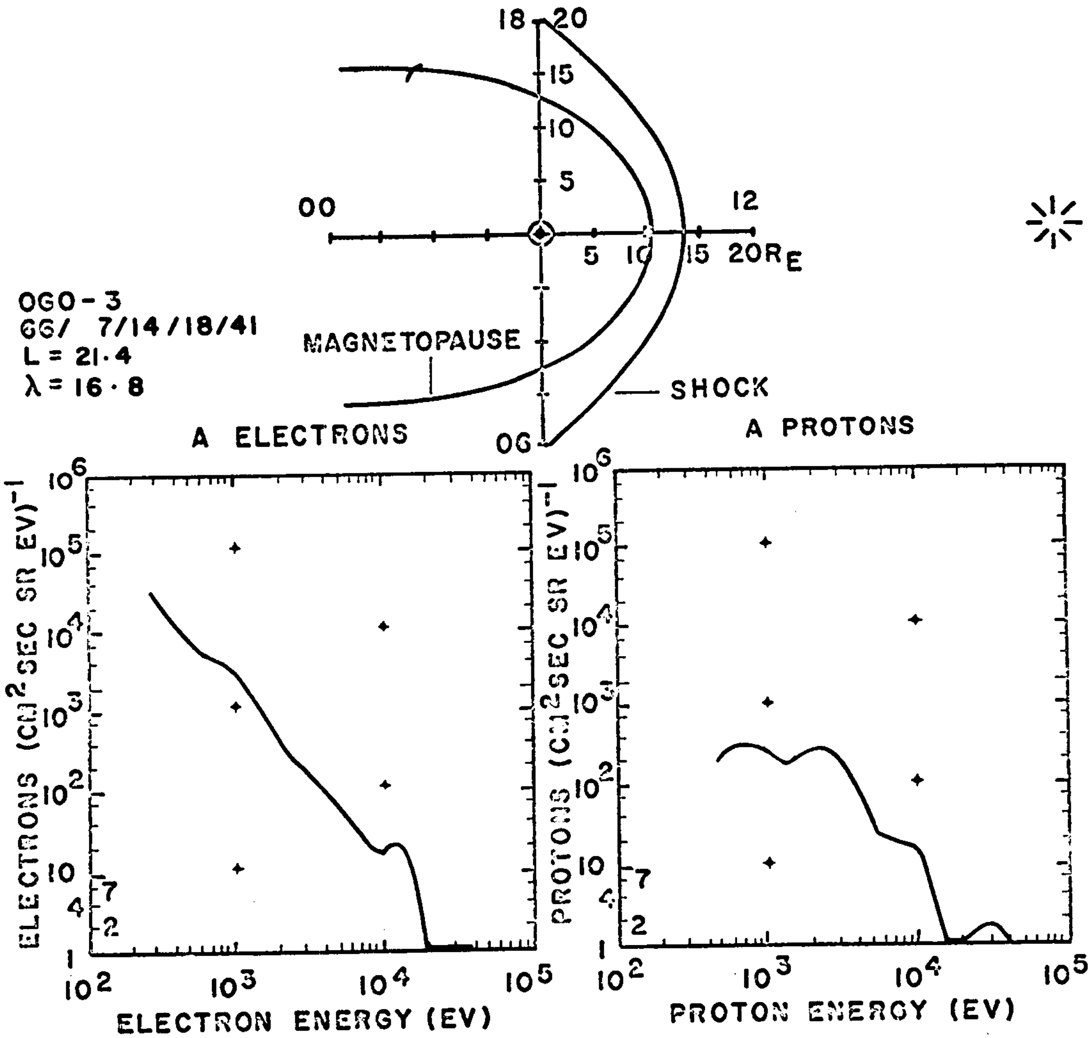


Figure 2

G67-1058

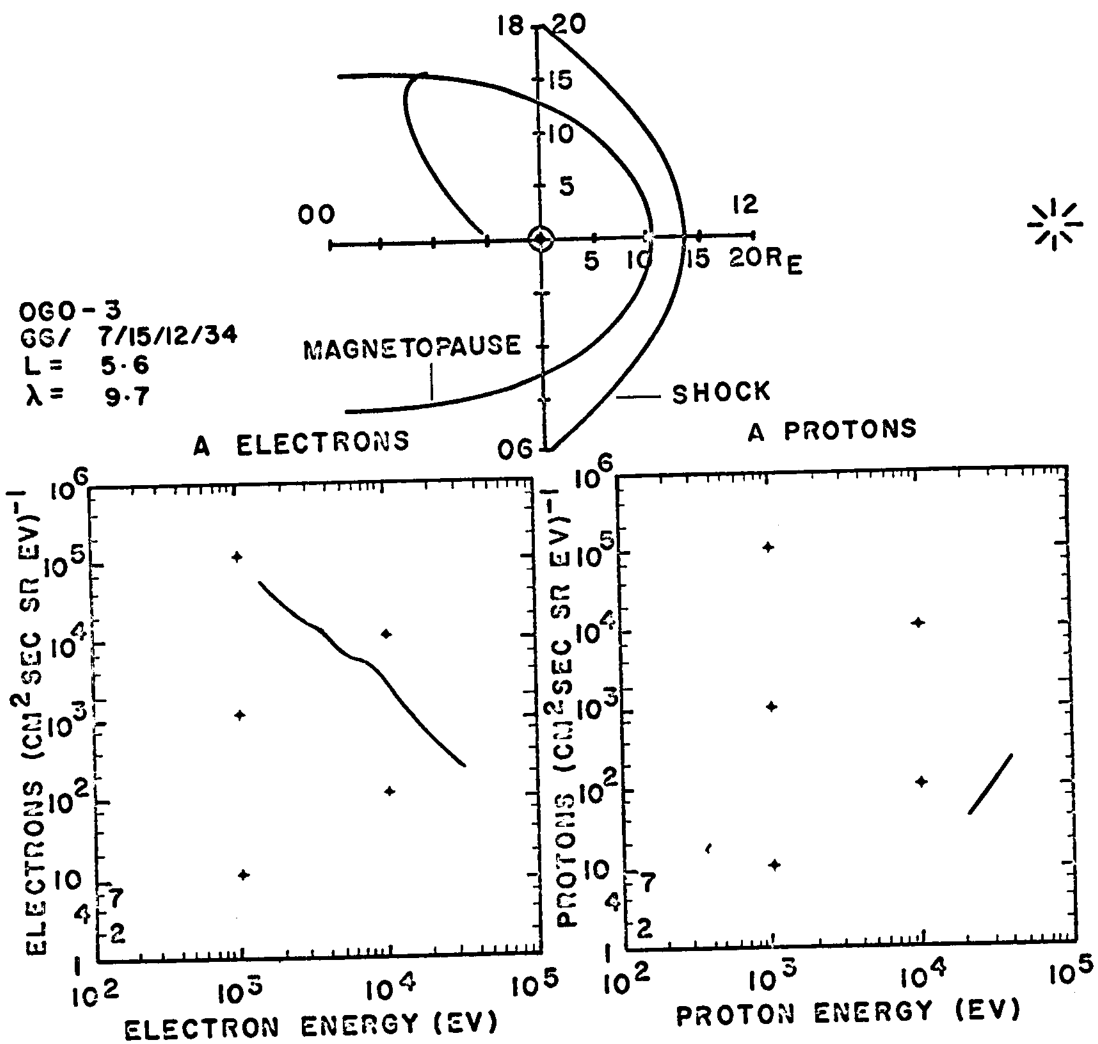


Figure 3

G67-1059

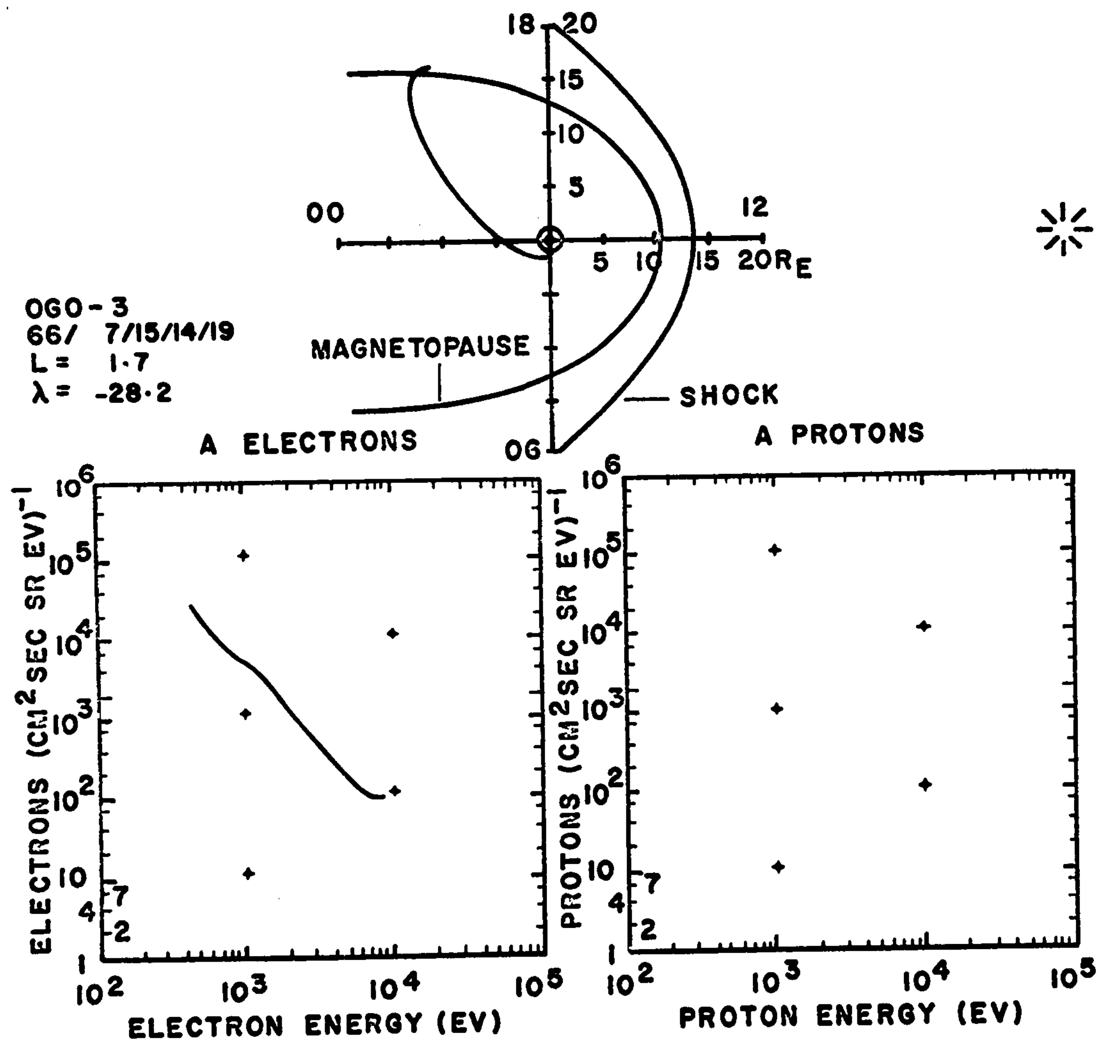


Figure 4

G67 - 1060

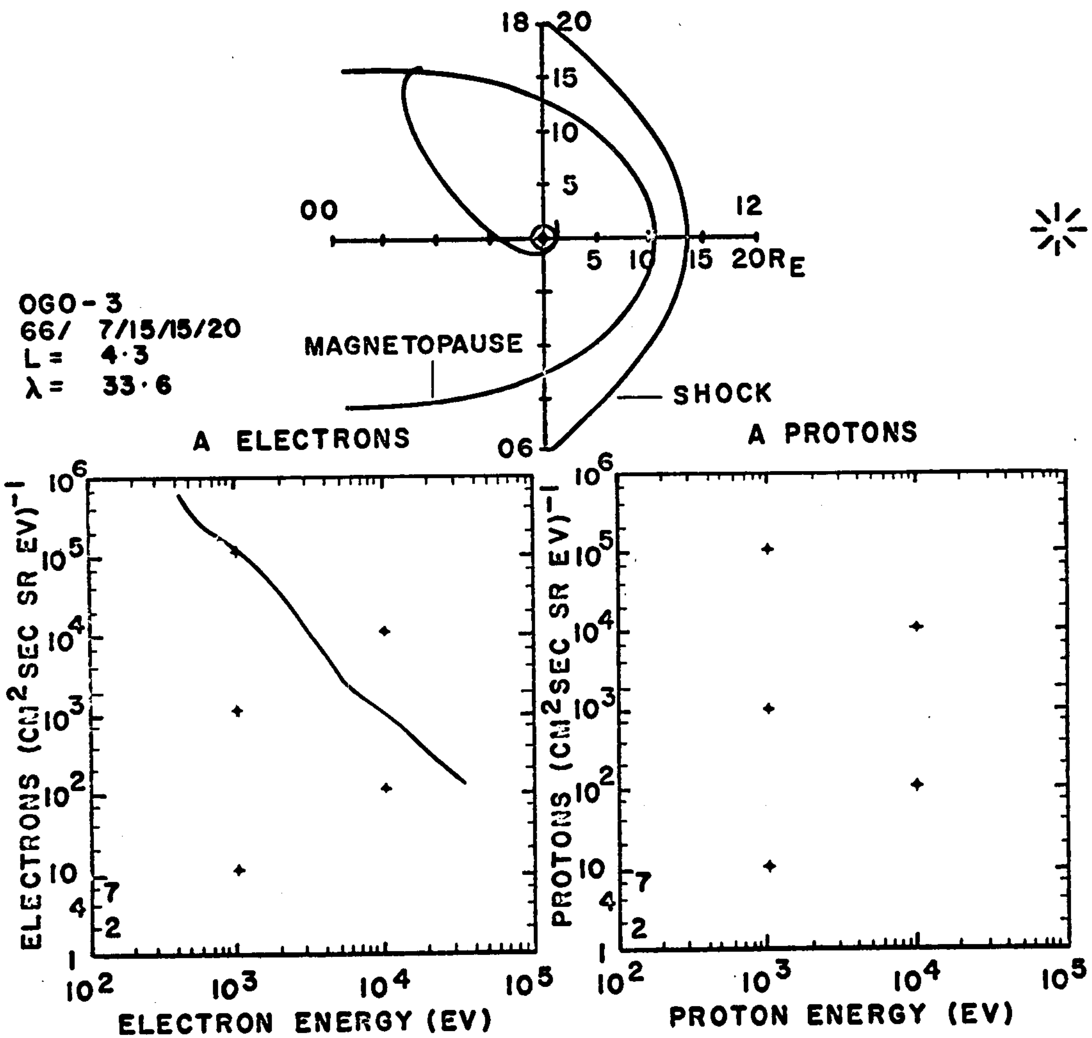
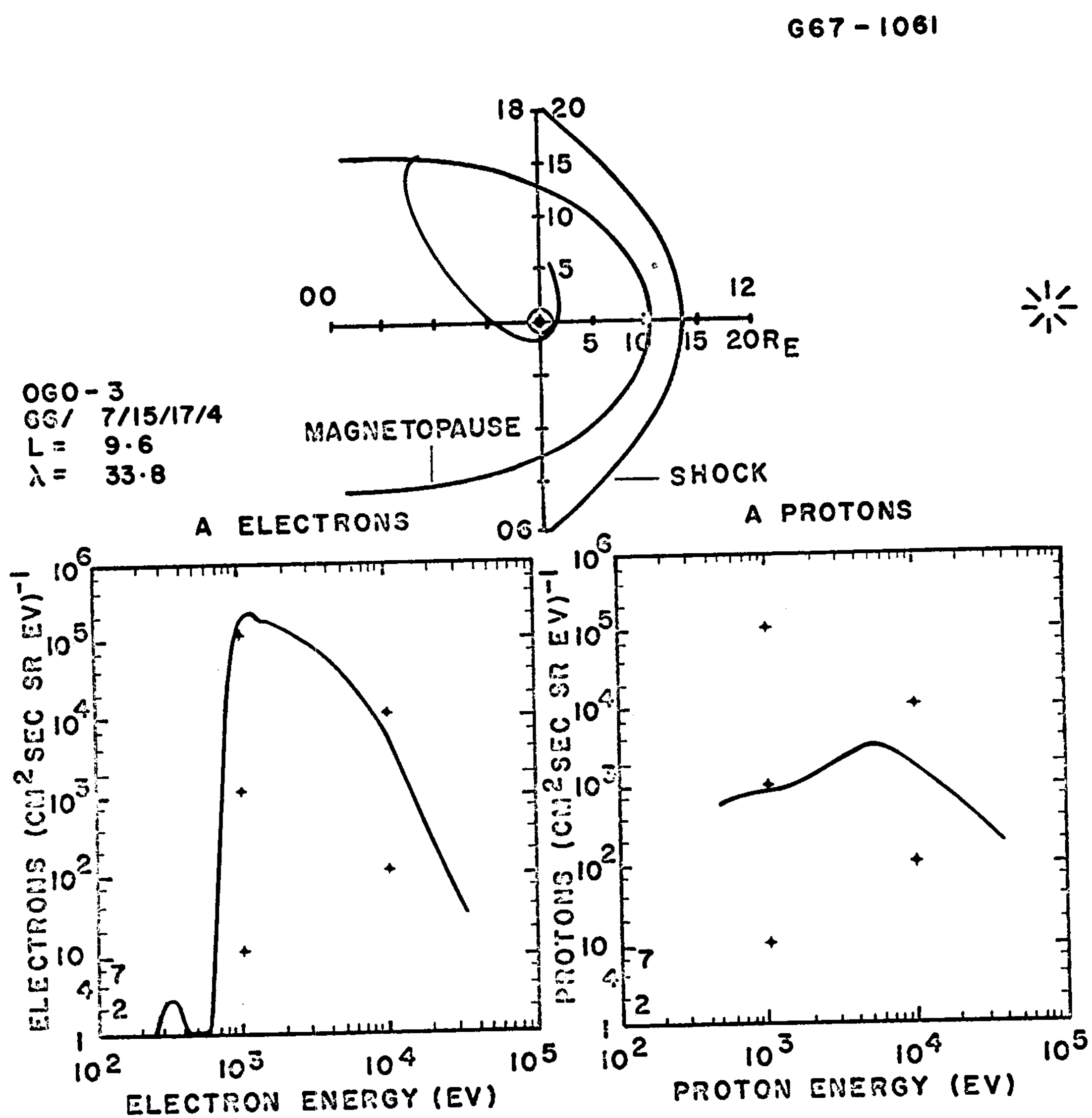


Figure 5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OGO-3
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λ = 33·8
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SHOCK
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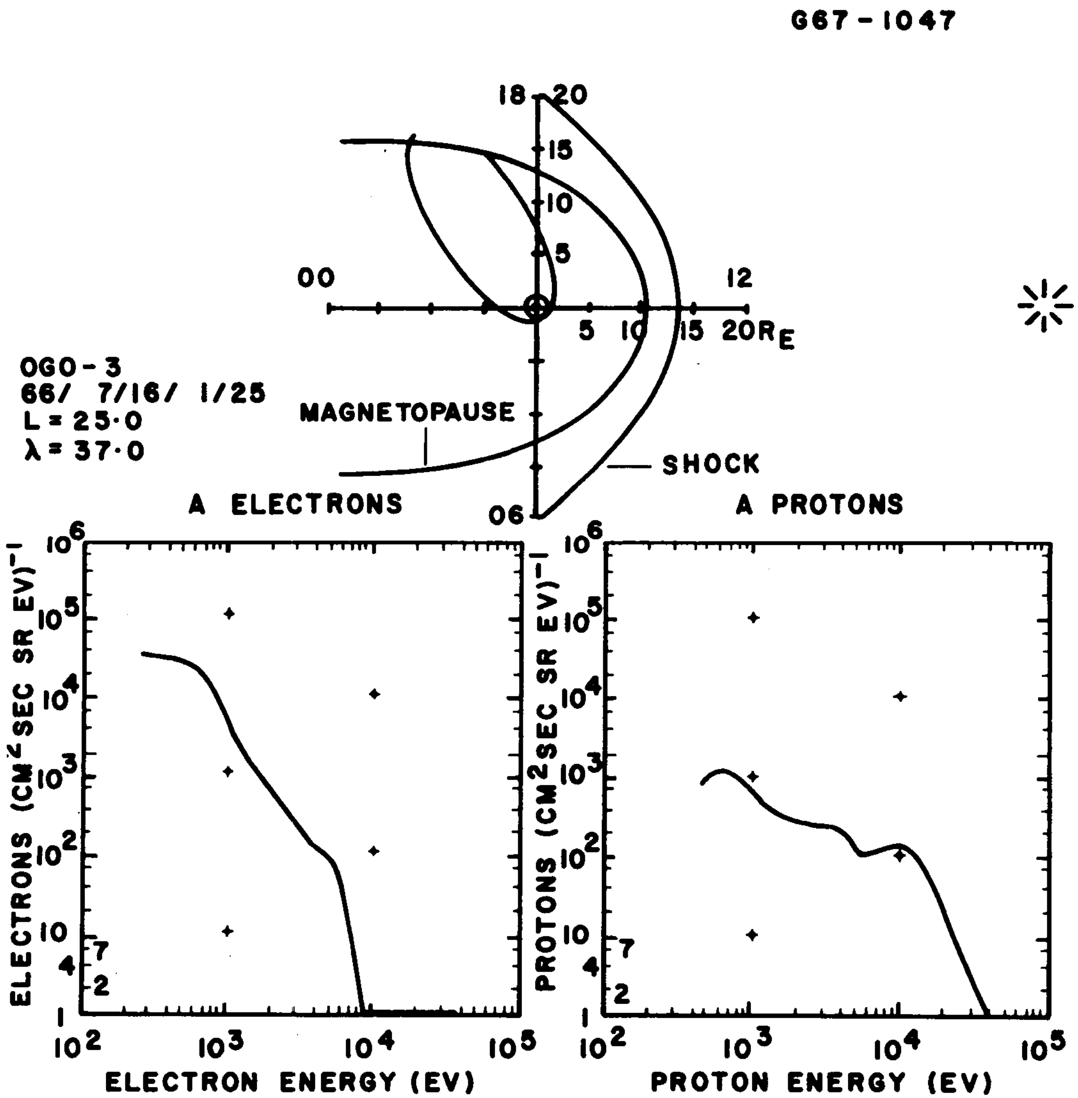
A ELECTRONS
A PROTONS
ELECTRONS (CM2SEC SR EV)-1
ELECTRON ENERGY (EV)
PROTONS (CM2SEC SR EV)-1
PROTON ENERGY (EV)

Figure 6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12
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20RE
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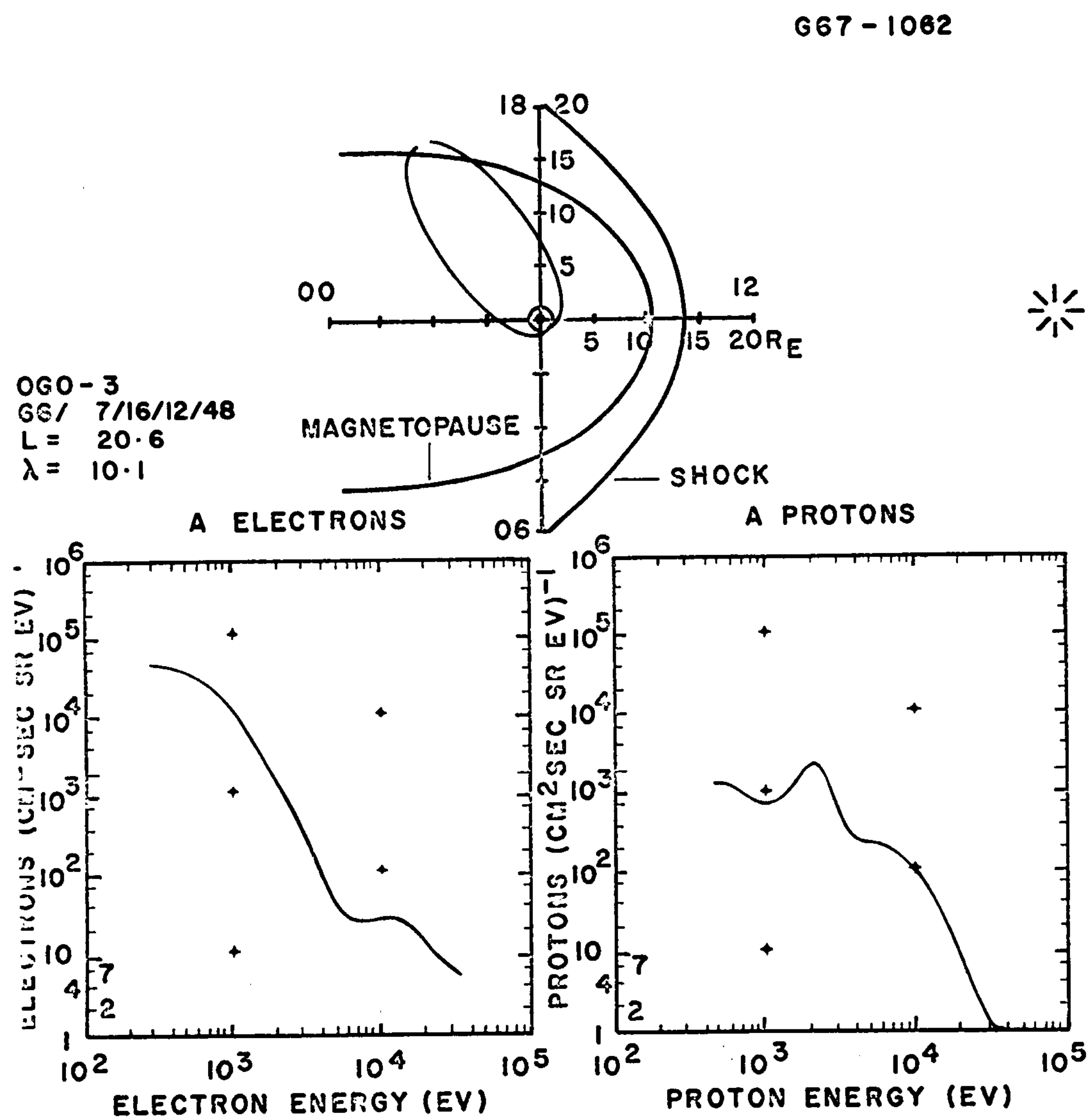
OGO-3
66/ 7/16/ 1/25
L = 25·0
λ = 37·0
MAGNETOPAUSE
SHOCK
A ELECTRONS
A PROTONS
ELECTRONS (CM²SEC SR EV)⁻¹
PROTONS (CM²SEC SR EV)⁻¹
ELECTRON ENERGY (EV)
PROTON ENERGY (EV)

Figure 7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λ = 10·1
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12
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20RE
MAGNETOPAUSE
SHOCK
A ELECTRONS
A PROTONS
ELECTRONS (CM²-SEC SR EV)⁻¹
PROTONS (CM²SEC SR EV)⁻¹
ELECTRON ENERGY (EV)
PROTON ENERGY (EV)

Figure 8

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A Cinematographic Display of Observations of Low-Energy Proton and Electron Spectra in the Terrestrial Magnetosphere.

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Progress November 1967

5. AUTHOR(S) (Last name, first name, initial)

FRANK, L. A. and W. L. Shope

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
November 1967	24	11

8a. CONTRACT OR GRANT NO. Nonr-1509(06) b. PROJECT NO. c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) U. of Iowa 67-67 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

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A massive series of observations of the differential energy spectra of proton and electron intensities over the energy range ~ 300 eV to 50 keV within the earth's magnetosphere and its environs has been obtained with an array of electrostatic analyzers borne on the earth-satellite OGO 3. In order to supplement the presently existing publications derived from these observations and to provide further insight into the distributions of low-energy charged particles within the earth's radiation zones over geocentric radial distances ~ 2 to 20 R_E (R_E, earth radii) we have utilized a SC 4020 microfilm plotter to construct a cinematographic display of the differential energy spectra of proton and electron intensities which spans a complete circuit of the spacecraft around the earth, or ~ 50 hours of substantially continuous observations beginning at 1330 U.T. on July 14, 1966. This cinematographic display comprises approximately 18,000 individual frames and summarizes some 550,000 intensity measurements. A description of the methods and graphic results is furnished as an aid in interpretation of this visual presentation of the observations.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Magnetosphere						
Outer Radiation Zone						
Geomagnetic Tail						

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